

## Vector boson and charmonia measurements in $p$ +Pb collisions with ATLAS at the LHC

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**Markus K. Köhler<sup>\*†</sup>**

*Weizmann Institute of Science*

*E-mail:* [markus.konrad.kohler@cern.ch](mailto:markus.konrad.kohler@cern.ch)

The production of electroweak bosons ( $Z$ ,  $\gamma$  and  $W$ ) and charmonia is sensitive to the initial-state geometry of heavy-ion collisions and to the parton distribution function with its potential nuclear modification. Since their leptonic decay products do not interact strongly, their kinematics are unmodified by the strongly interacting medium, which can be created in a heavy-ion collision.

We report on the latest results of the ATLAS Collaboration on electroweak boson and charmonia production in  $p$ +Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. Production yields of  $Z$  and  $W$  bosons are presented as a function of (pseudo-)rapidity in different centrality bins. The forward-backward ratio of  $J/\psi$  is shown as a function of transverse momentum and center-of-mass rapidity.

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<sup>\*</sup>Speaker.

<sup>†</sup>On behalf of the ATLAS Collaboration

## 1. Introduction

Heavy-ion collisions at ultrarelativistic energies, such as performed at the LHC at CERN, are believed to result in a phase transition from hadronic to partonic degrees of freedom and form a state of matter called Quark-Gluon Plasma (QGP), see e.g. Ref. [1] for a recent review.

It is known from previous experiments that color charged particles are suppressed in heavy-ion collisions [2], which is attributed to the parton energy-loss by traversing through the hot and dense medium [3]. However, particles which are created in hard scatterings before the QGP is formed and whose decay products do not interact strongly provide the possibility to study heavy-ion collisions unmodified by the medium. So the production yield of electroweak bosons, such as prompt photons or  $W$  and  $Z$  bosons, can be described by a superposition of nucleon-nucleon collisions scaled by the mean number of collisions calculated within the Glauber model in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV [4]. These measurements are consistent to NLO QCD calculations using a particle distribution function (PDF), which does not incorporate nuclear modifications. However, the measurements do not allow to exclude nuclear modifications within their precision.

To study PDFs and their potential nuclear modifications, it is advantageous to study asymmetric collision systems like  $p+Pb$  collisions [5]. Since nuclear modifications in  $p+Pb$  collisions have a larger impact on the resulting boson distributions, measurements can better discriminate between PDFs which incorporate nuclear modifications and those which do not.

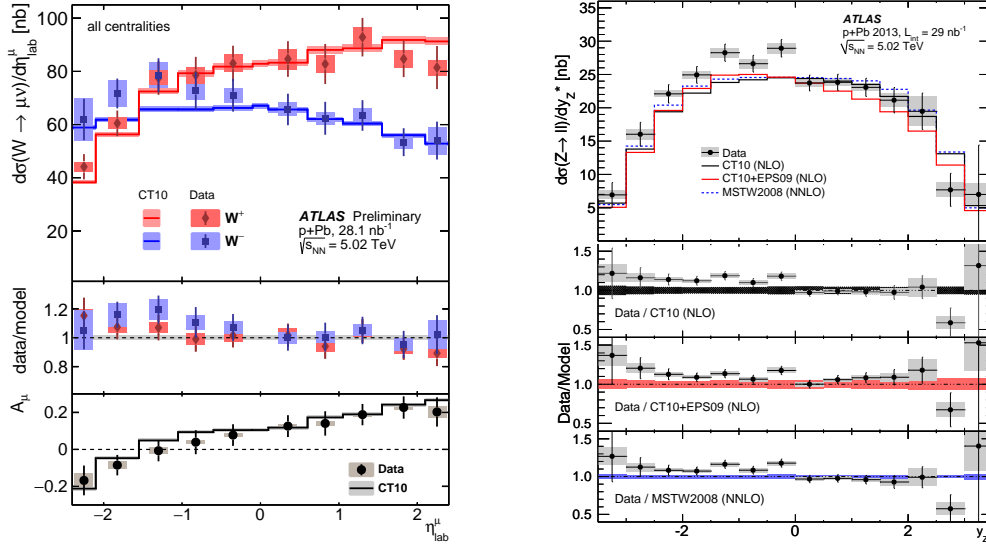
As opposed to electroweak bosons, heavy quarks, such as charm or beauty, do interact with the hot and dense matter. In central Pb+Pb collisions,  $J/\psi$  production is suppressed relative to  $pp$  collisions [6]. To distinguish the impact of initial state and final state effects, charmonia production in  $p+Pb$  collisions serves as a control measurement for Pb+Pb collisions.

These proceedings report on  $W$  boson,  $Z$  boson and charmonia measurements in  $p+Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV collected by ATLAS<sup>1</sup> [7] at the LHC corresponding to an integrated luminosity of  $28 \text{ nb}^{-1}$ . The Pb beam had an energy of 1.57 TeV per nucleon and the opposing proton beam had an energy of 4 TeV. As a convention, results are shown with positive rapidity corresponding to the proton beam direction and negative rapidity corresponding to the direction of the Pb beam, ‘Pb-going’ side.

## 2. Electroweak bosons

The  $W$  boson production is measured in its muon decay channel. Muons are reconstructed in the Inner Detector and the Muon Spectrometer and combined using a  $\chi^2$  minimization. The neutrino is identified by the signature of the missing transverse energy  $E_T^{\text{miss}}$ . The production yields have been measured within the fiducial volume of  $p_T^\mu > 25 \text{ GeV}$ ,  $E_T^{\text{miss}} > 25 \text{ GeV}$ ,  $0.1 < |\eta^\mu| < 2.4$  and  $m_T = \sqrt{2p_T^\mu E_T^{\text{miss}} (1 - \cos \Delta\phi_{\mu, E_T^{\text{miss}}})} > 40 \text{ GeV}$ , where  $\Delta\phi_{\mu, E_T^{\text{miss}}}$  is the azimuthal angle between the muon and the missing transverse energy. The background, consisting of muons from multijet collisions and other electroweak muon sources, is estimated by fitting signal and background tem-

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\text{Ln} \tan(\theta/2)$ .



**Figure 1:** Cross section measurements of  $W$  (left panel) and  $Z$  (right panel) bosons in  $p+Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV as a function of (pseudo-) rapidity. Data is compared to NLO QCD calculations incorporating the PDF CT10. In addition,  $Z$  boson production is also compared to MSTW2008 and to CT10 incorporating nuclear modifications EPS09. Figures taken from [8] and [9].

plates to the measured  $E_T^{\text{miss}}$  distribution.

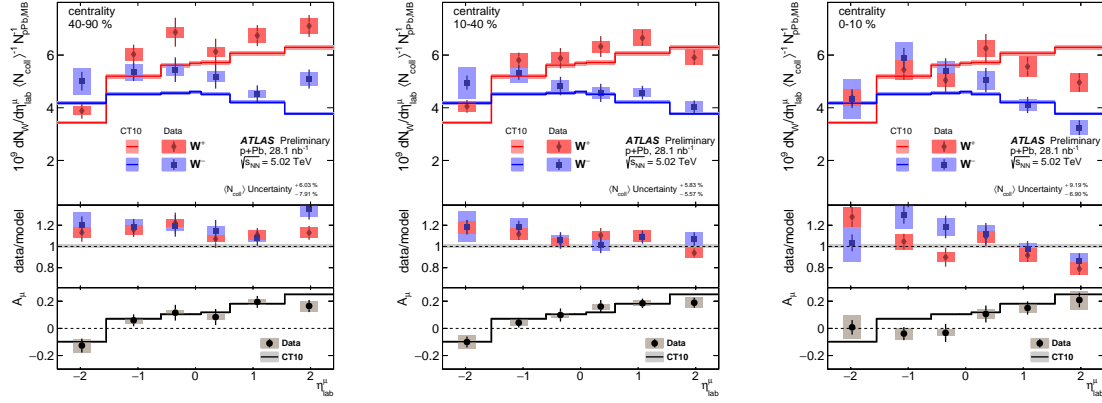
The cross section is calculated separately for  $W^+$  and  $W^-$ . The differences between both charges can be expressed by the lepton charge asymmetry  $A_\mu$ , and is given by

$$A_\mu(\eta^\ell) = \frac{dN_{W^+}/d\eta^\ell - dN_{W^-}/d\eta^\ell}{dN_{W^+}/d\eta^\ell + dN_{W^-}/d\eta^\ell}, \quad (2.1)$$

where  $N_{W^+}$  and  $N_{W^-}$  is the efficiency corrected and background subtracted number of  $W^+$  and  $W^-$ .  $Z$  bosons were measured via their dielectron and dimuon decay channel. Electrons are measured within the pseudo-rapidity range  $|\eta^e| < 2.5$ , excluding the transition region between the barrel and the endcap calorimeter  $1.37 < |\eta^e| < 1.52$ . They are then required to have  $E_T > 20$  GeV. Muons are analyzed within the fiducial volume  $p_T > 20$  GeV and  $|\eta^\mu| < 2.4$ . The combinatorial background is estimated by the amount of like-sign pairs. After the dielectron and dimuon channel have been found consistent, both channels are combined with weights set by their corresponding uncertainties.

In Figure 1, the cross section of  $W$  and  $Z$  bosons is shown as a function of  $\eta^\mu$  and the center-of-mass rapidity<sup>2</sup>  $y^*$ . Data is compared to calculations using the PDF CT10 [10] and (in the case of the  $Z$  boson), MSTW2008 [11] and CT10 incorporating the nuclear modification EPS09 [12]. Additionally, the ratio between data and the calculations are shown. In the cases of the  $Z$  and  $W^-$  bosons, the measured cross sections exceed the calculations in the Pb-going side. Consequently, the lepton charge asymmetry undershoots the calculations in the Pb-going side. It should be noted that in the case of the  $Z$  boson, the calculations of CT10 incorporating the nuclear modifications

<sup>2</sup>The center-of-mass rapidity  $y^*$  is defined as  $y^* = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ , where  $E$  and  $p_z$  are the energy and the component of the momentum along the proton beam direction in the nucleon-nucleon center-of-mass frame.



**Figure 2:** The  $W$  boson production is shown as a function of the muon pseudo-rapidity in the laboratory frame for the centrality 40 – 90 % (left panel), 10 – 40 % (middle panel) and 0 – 10 % (right panel). In the upper panels, the production rate normalized to the number of minimum-bias events and the average number of binary nucleon-nucleon collision per centrality is shown. Data is compared to POWHEG calculations incorporating CT10. The ratio of data and calculations is shown in the middle panel. The lower panel shows the lepton charge asymmetry. Figures taken from [8].

EPS09 described the data best [9]. The same behavior for the cross section of electroweak bosons was also seen by the CMS Collaboration [13, 14].

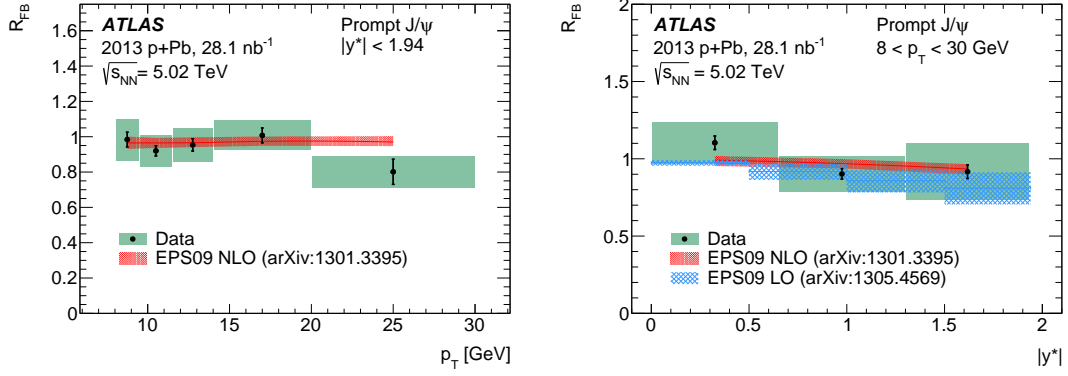
In addition to the cross sections, the centrality dependence of  $W$  and  $Z$  production is investigated. The values for  $\langle N_{\text{coll}} \rangle$  are calculated using the Glauber MC simulation [15] using the total transverse energy deposited in the forward calorimeter (FCal) in the Pb-going direction. In addition, values for  $\langle N_{\text{coll}} \rangle$  are calculated using Glauber-Gribov Color Fluctuations (GGCF) models, see e.g. [16]. In presence of a hard scattering process, such as  $W$  or  $Z$  boson production, the underlying event is increased. Consequently, more energy is deposited in the FCal, leading to a potential bias of the centrality calculation. Therefore a correction was applied, following Ref. [17].

In Figure 2, the  $W$  boson production as a function of  $\eta^\mu$  is shown for peripheral (40 – 90 %), mid-central (10 – 40 %) and central (0 – 10 %) collisions for the case of centrality calculations within the Glauber model and corrected for the centrality bias. The data shown is compared with calculations incorporating the CT10 PDF. Data is normalized to number of minimum-bias events and  $\langle N_{\text{coll}} \rangle$  within the centrality class.

In the most peripheral centrality class, data is consistently exceeding the calculations, which might be due the uncertainty in calculation of  $\langle N_{\text{coll}} \rangle$ . However, there appears to also be change of slope within the most central events. While in peripheral and mid-central collisions the lepton charge asymmetry is well described by the CT10 calculations, in the most central event class there is a discrepancy in differential cross section in the same rapidity range where it deviates from the model as shown in Figure 1.

### 3. Charmonia

The measurement of  $J/\psi$  production in  $p+Pb$  collisions was carried out in the dimuon channel. Muons are required to have  $p_T > 4$  GeV and be within the acceptance of  $|\eta| < 2.4$ . Non-prompt



**Figure 3:** Forward-backward production ratio  $R_{FB}$  of prompt  $J/\psi$  as a function of  $J/\psi$  transverse momentum (left panel) and as a function of center-of-mass pseudo-rapidity (right panel). Figures taken from [18].

$J/\psi$  contributions, i.e.  $J/\psi$  from decay chains of  $b$ -quarks, are separated by using the ‘pseudoproper time’,  $\tau = L_{xy} \frac{m_{\mu\mu}}{p_T}$ , where  $p_T$ ,  $m_{\mu\mu}$  and  $L_{xy}$  are the dimuon transverse momentum, its invariant mass and the signed transverse distance between the primary vertices and the  $J/\psi$  decay vertex, respectively.

In asymmetric collision systems, such as  $p+Pb$  collisions, the cross sections might not be symmetric with respect to  $y^* = 0$ . These asymmetries of the cross sections can be quantified by the forward-backward production ratio  $R_{FB}$ , which is defined as

$$R_{FB}(p_T, y^*) = \frac{d^2\sigma(p_T, y^* > 0)/dp_T dy^*}{d^2\sigma(p_T, y^* < 0)/dp_T dy^*}. \quad (3.1)$$

In Figure 3,  $R_{FB}$  of prompt  $J/\psi$  is shown as a function of the  $J/\psi$  transverse momentum and the center-of-mass rapidity within  $8 < p_T < 30$  GeV and  $|y^*| < 1.94$ . The experimental results are consistent with unity within the experimental uncertainties and no significant dependence on  $p_T$  or  $y^*$  is found. Data is compared with PDFs including nuclear modifications (EPS09) in LO and NLO. The calculations are found to be consistent with data.

#### 4. Summary

We presented the latest results on  $W$  boson,  $Z$  boson and charmonia production in  $p+Pb$  collisions at  $\sqrt{s_{NN}} = 5.02$  TeV measured with the ATLAS detector at LHC.

NLO pQCD calculations describe the  $W$  and  $Z$  boson production well, except in the Pb-going direction, where a small excess seems to appear. This behavior is best described by PDFs including nuclear modifications.

The forward-backward ratio of prompt  $J/\psi$  is shown and found to be consistent with unity within experimental uncertainties. This behavior is reproduced by two PDF sets incorporating EPS09 modifications.

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